# Storage lifetime of ultracold neutrons in superfluid helium between 1.0 K and 1.8 K

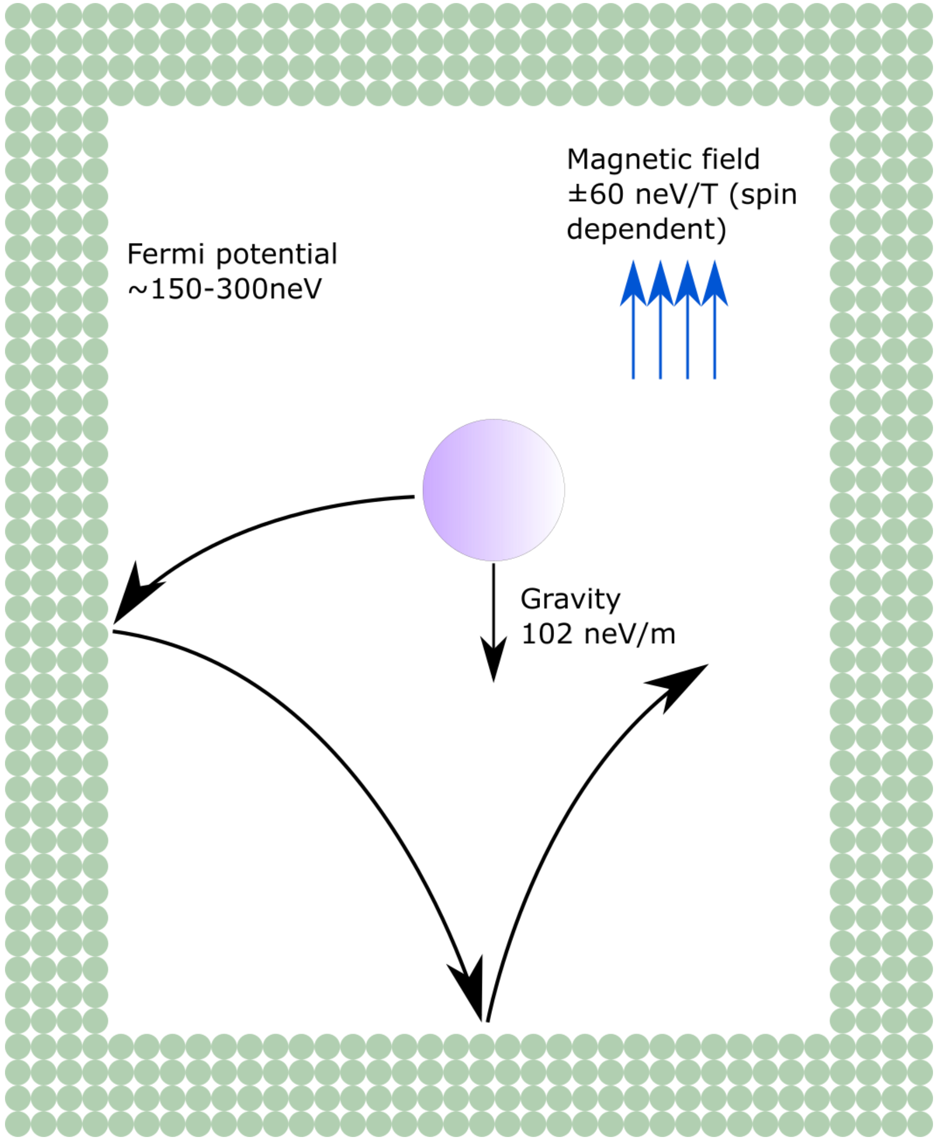
Sean Vanbergen – TUCAN Collaboration – CAP Congress 2023

# Ultracold Neutrons (UCN)

- UCN have kinetic energies < 300 neV (>50 nm wavelength)
- For UCN, bulk materials behave as a constant Fermi potential

$$U = V + iW$$

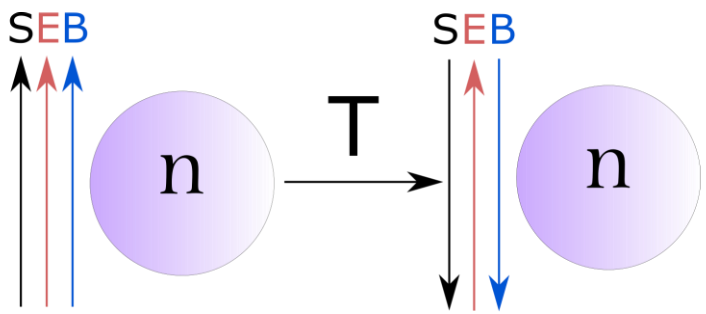
- Magnetic and gravitational potentials comparable to kinetic energies
- Can be confined for long periods of time in a small space – great for precision experiments!



# Ultracold Neutrons (UCN)

Broad potential for testing the standard model and probing new physics!

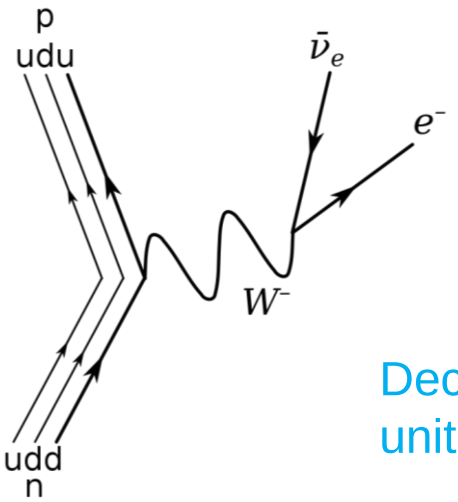
## Neutron Electric Dipole Moment



$$H = -\mu_n \boldsymbol{B} \cdot \frac{\boldsymbol{S}}{S} - d_n \boldsymbol{E} \cdot \frac{\boldsymbol{S}}{S} \rightarrow H = -\mu_n \boldsymbol{B} \cdot \frac{\boldsymbol{S}}{S} + d_n \boldsymbol{E} \cdot \frac{\boldsymbol{S}}{S}$$

T and CP symmetry-violating physics

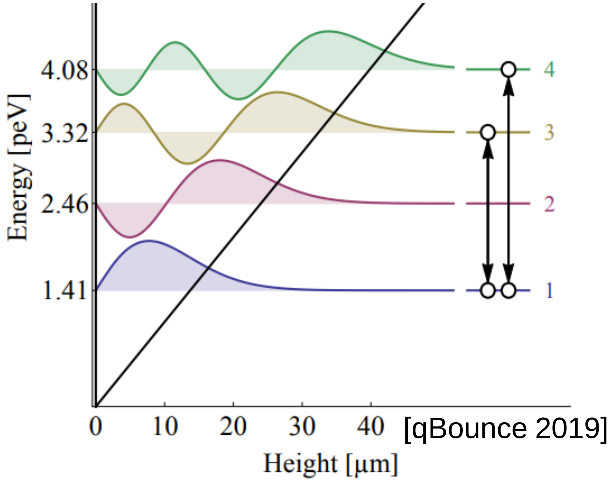
## Neutron Beta Decay



$$|V_{ud}|^2 = \frac{4908}{\tau_n(1+3\lambda^2)}$$

Decay correlations, test of CKM unitarity

## Gravitational Resonance Spectroscopy



[qBounce 2019]

$$\frac{\hbar^2}{2m} \nabla\psi(z) + mgz\psi(z) = E\psi(z)$$

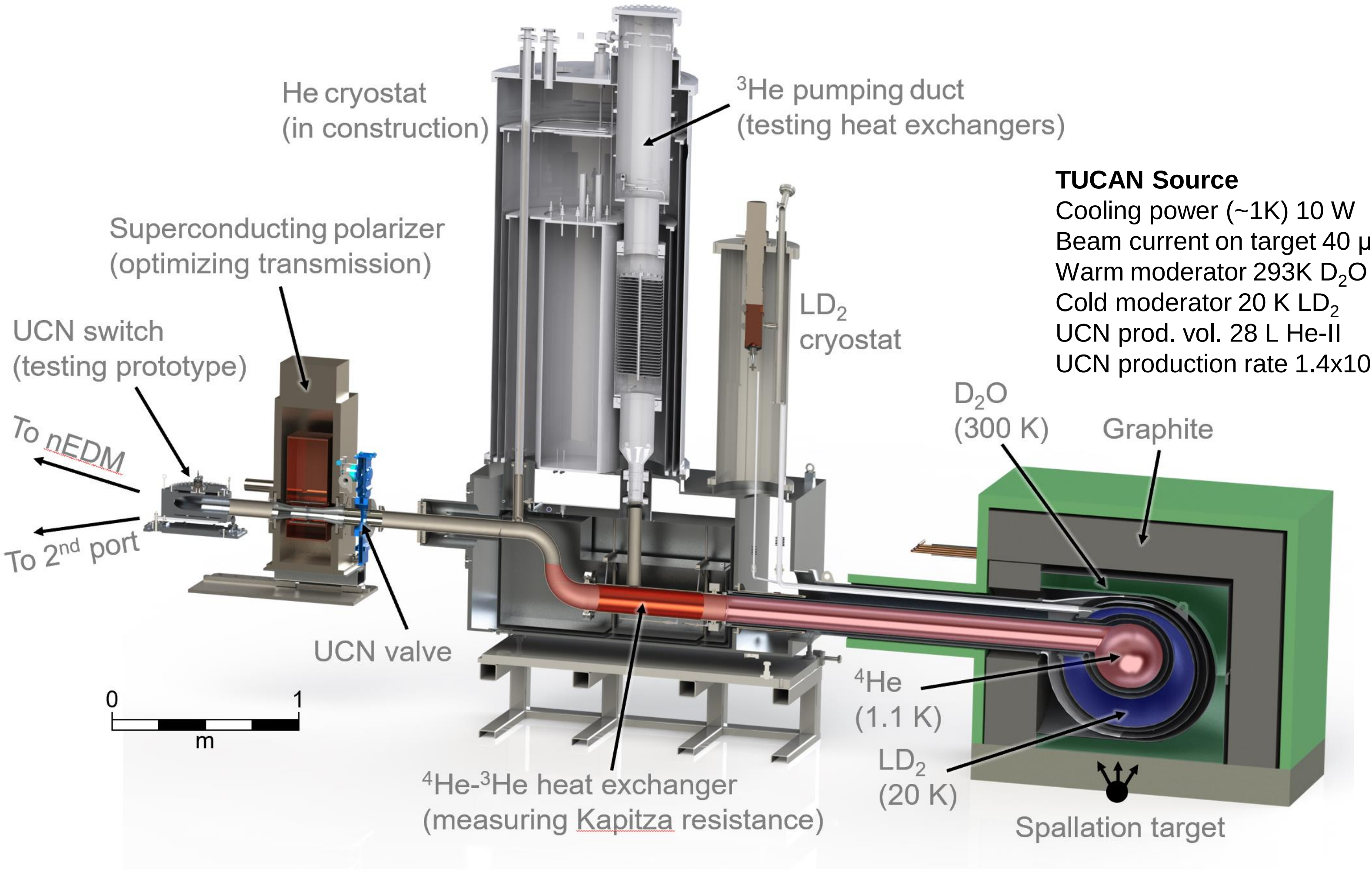
Sensitive to 5th forces, modified gravity, ALPs

# The TRIUMF UltraCold Advanced Neutron Source

The TUCAN Collaboration is building a new UCN source aiming to achieve the greatest-ever density of UCN in experiments

Production sequence:

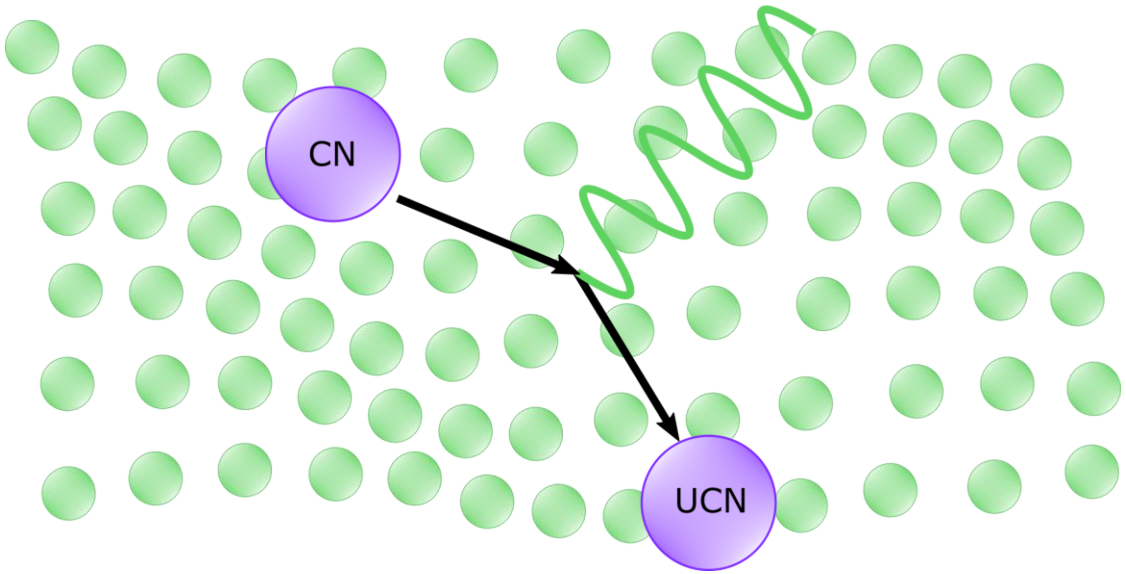
1. Production of high energy neutrons by spallation (MeV)
2. Moderation to cold energies (meV)
3. Superthermal conversion to UCN (neV) in superfluid helium (He-II)

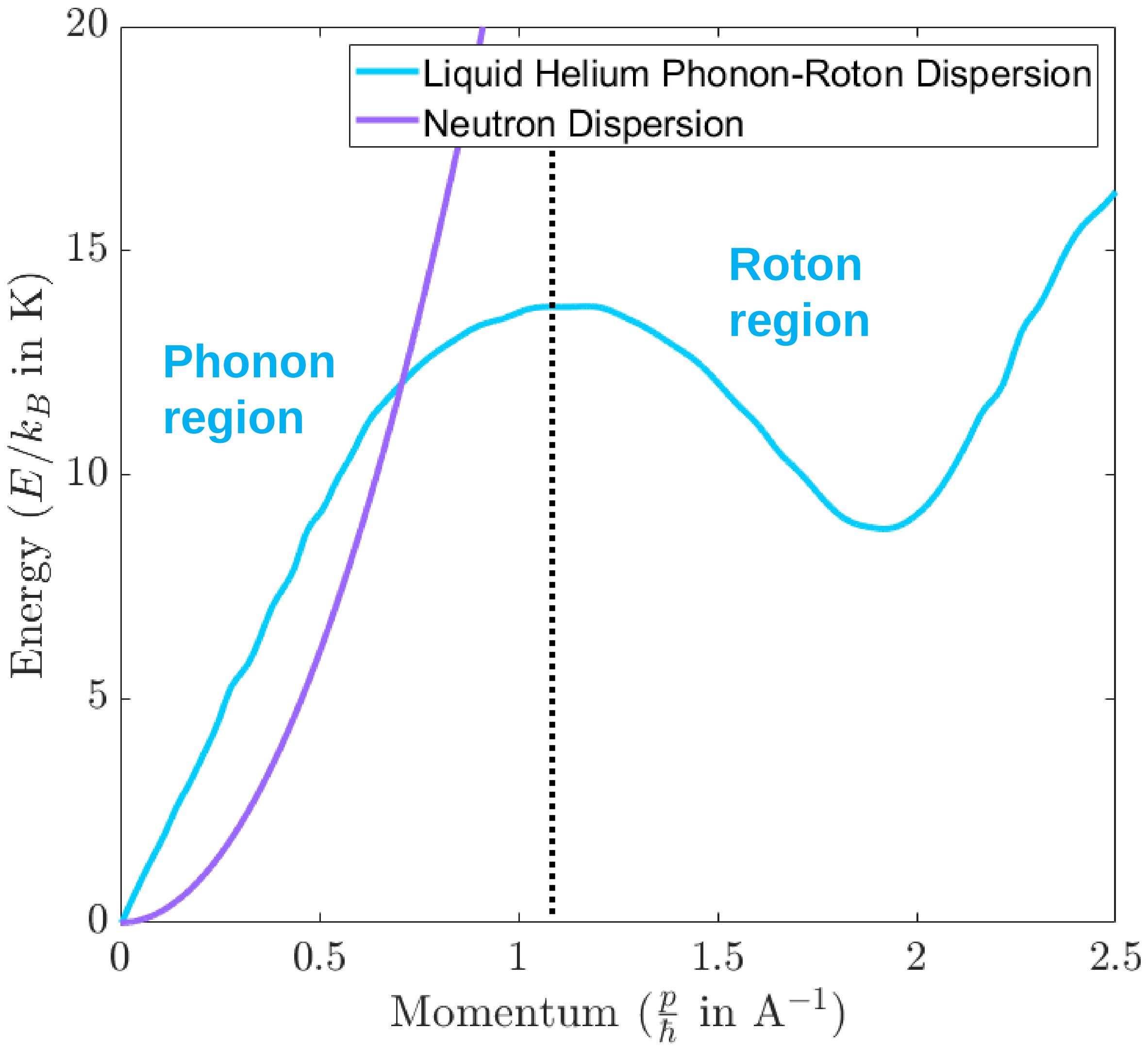


**TUCAN Source**
Cooling power (~1K) 10 W
Beam current on target 40 μA
Warm moderator 293K $D_2O$
Cold moderator 20 K $LD_2$
UCN prod. vol. 28 L He-II
UCN production rate $1.4 \times 10^7$ $s^{-1}$

# Downscattering: Production of UCN in He-II

- Cold neutrons are converted to ultracold neutrons by downscattering in He-II
- Emission of a phonon into the bulk superfluid



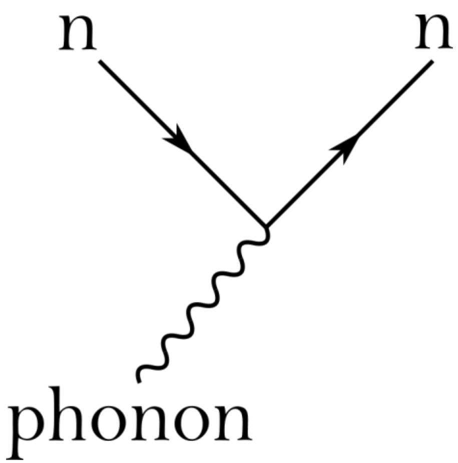


# Upscattering: Losses of UCN in He-II

- Reverse process – absorption of excitations – converts UCN back to cold neutrons

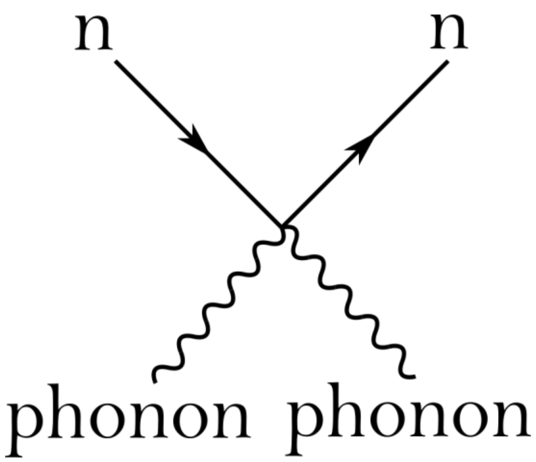
**Single-phonon process**

$$\tau^{-1}_{1-\mathrm{ph}} = Ae^{-E^*/T}$$



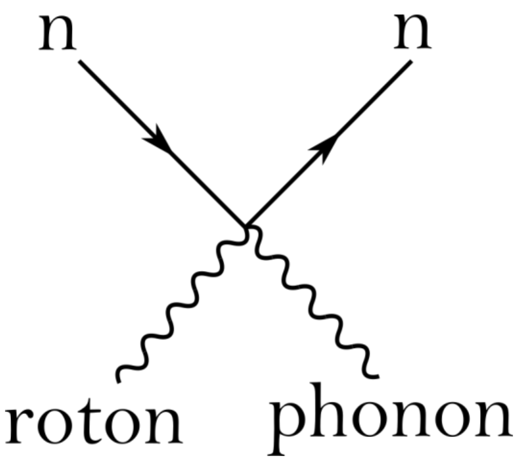
**Two-phonon process**

$$\tau^{-1}_{2-\mathrm{ph}} = BT^7$$



**Roton-phonon process**

$$\tau^{-1}_{\mathrm{r-ph}} = CT^{3/2}e^{-\Delta/T}$$

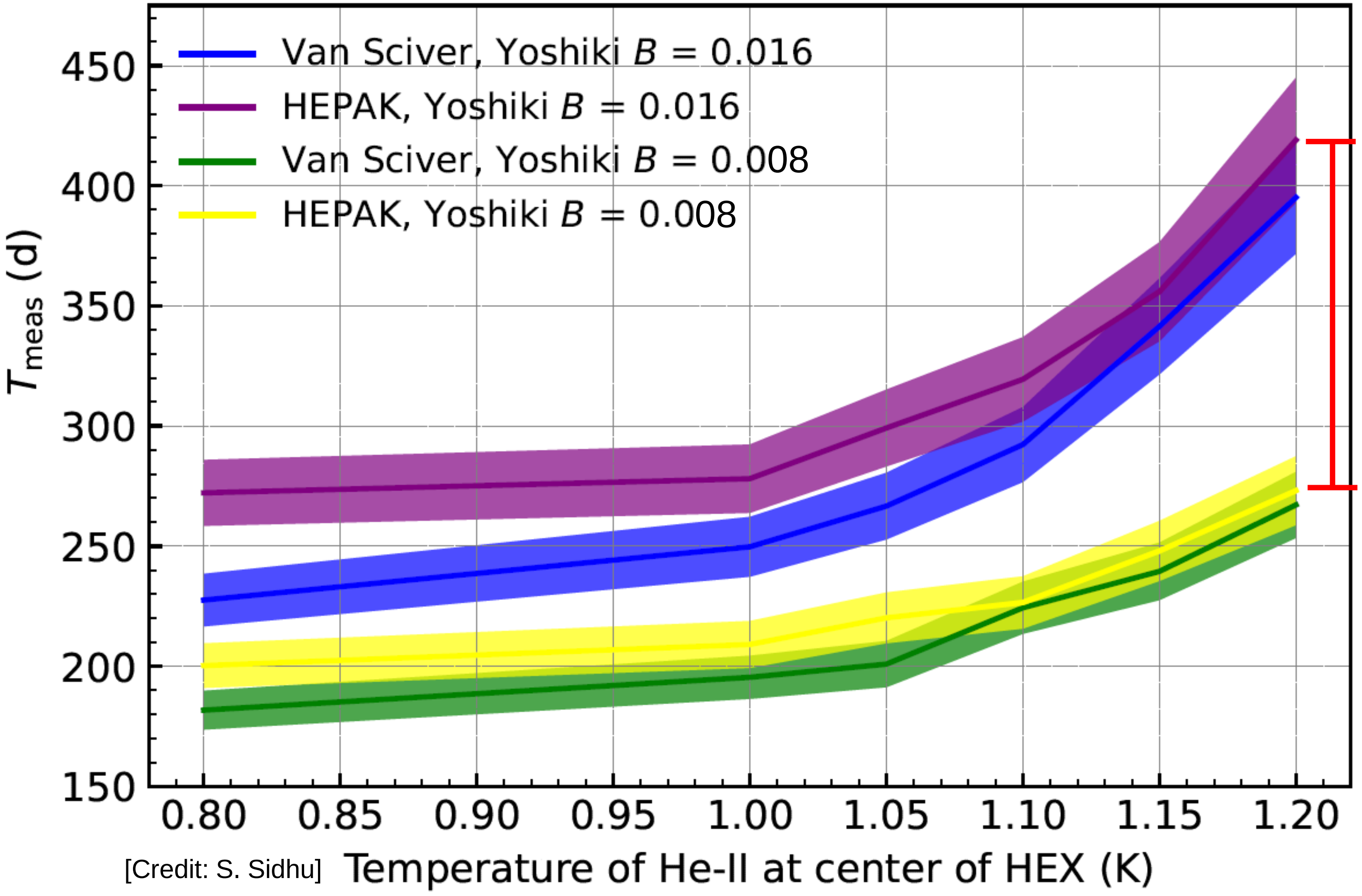


- At 1 K, theory values $\tau^{-1}_{1-\mathrm{ph}} = 0.0008\ \mathrm{s}^{-1}$, $\tau^{-1}_{2-\mathrm{ph}} = 0.0076\ \mathrm{s}^{-1}$, $\tau^{-1}_{\mathrm{r-ph}} = 0.0022\ \mathrm{s}^{-1}$
- Experimentally, $\tau^{-1}_{2-\mathrm{ph}}$ is sufficient to describe the losses, with $0.004 < B < 0.016\ \mathrm{K}^{-7}\mathrm{s}^{-1}$,

[Leung 2016 arXiv:1507.07475]

# Impact of *B* on nEDM Experimental Sensitivity

**Days of data-taking to reach TUCAN EDM $10^{-27}$ ecm sensitivity**



[Credit: S. Sidhu]

TUCAN goal is 400 days

Up to ~150 days difference between $B = 0.008\ \mathrm{K}^{-7}\mathrm{s}^{-1}$ and $B = 0.016\ \mathrm{K}^{-7}\mathrm{s}^{-1}$

More on the predicted sensitivity: S. Sidhu, et. al., EPJ Web of Conferences **282**, 01015 (2023)

https://doi.org/10.1051/epjconf/202328201015

# Prototype UCN Source at TRIUMF (2017-2019)

- 2.5% of beam power and 28% of He-II volume
- Heavy ice vs $LD_2$ moderator
- Used for UCN source development

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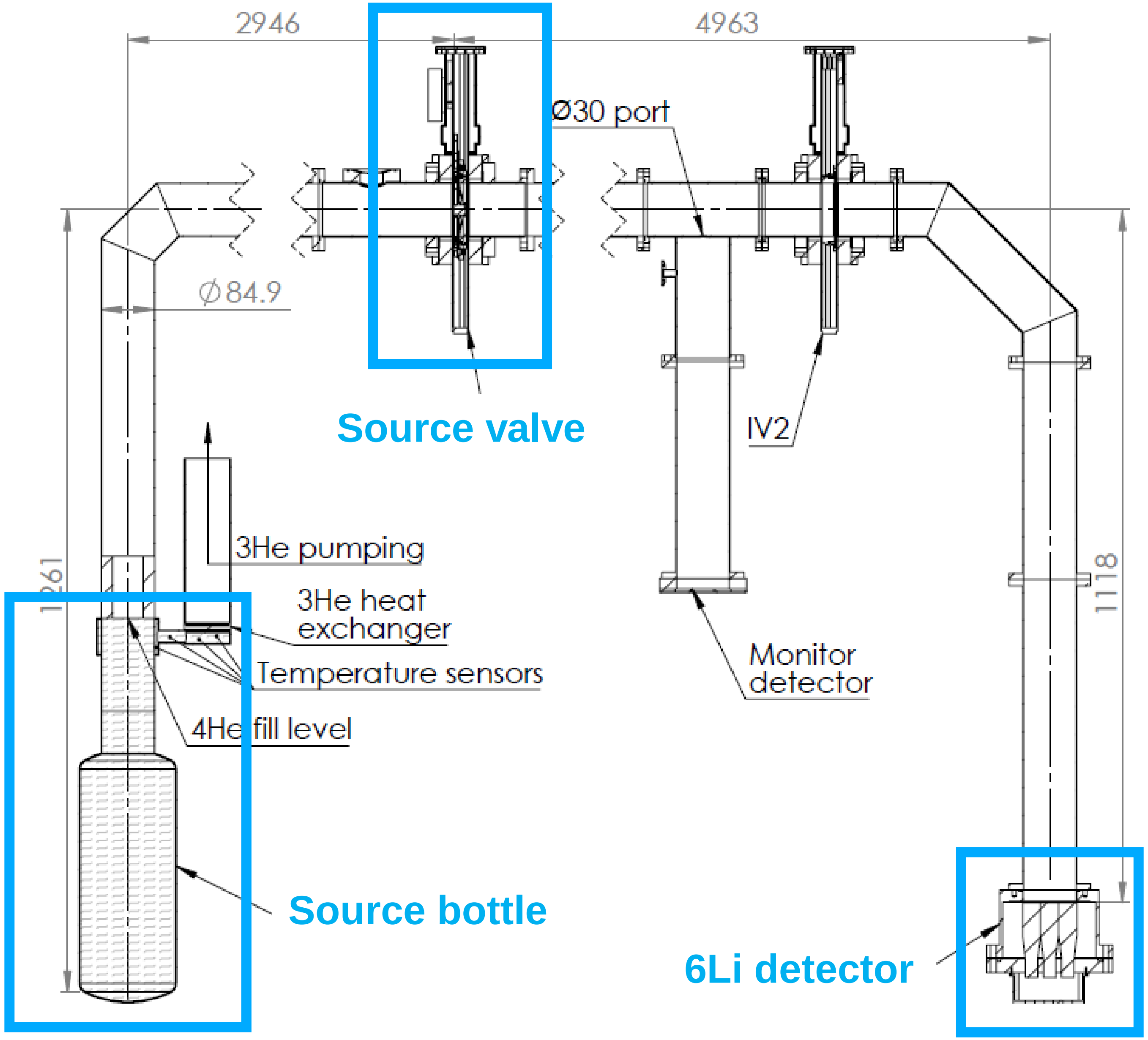
# Storage Lifetime Measurement

1. **Production** with source valve closed and beam on to fill source with UCN
2. **Storage** with beam off and source valve closed
3. **Detection** with beam off and source valve open



Source valve

Source bottle

6Li detector

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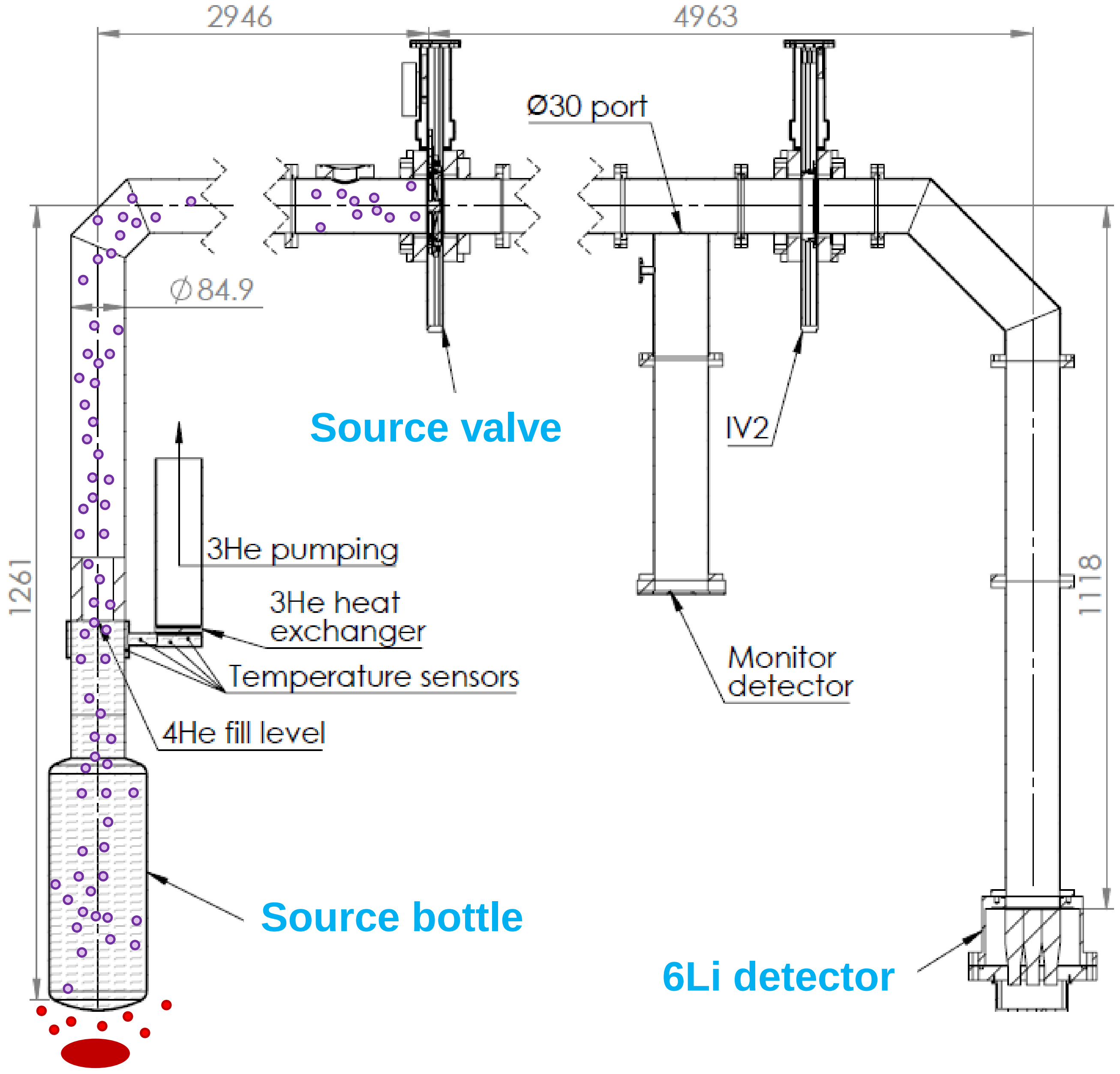

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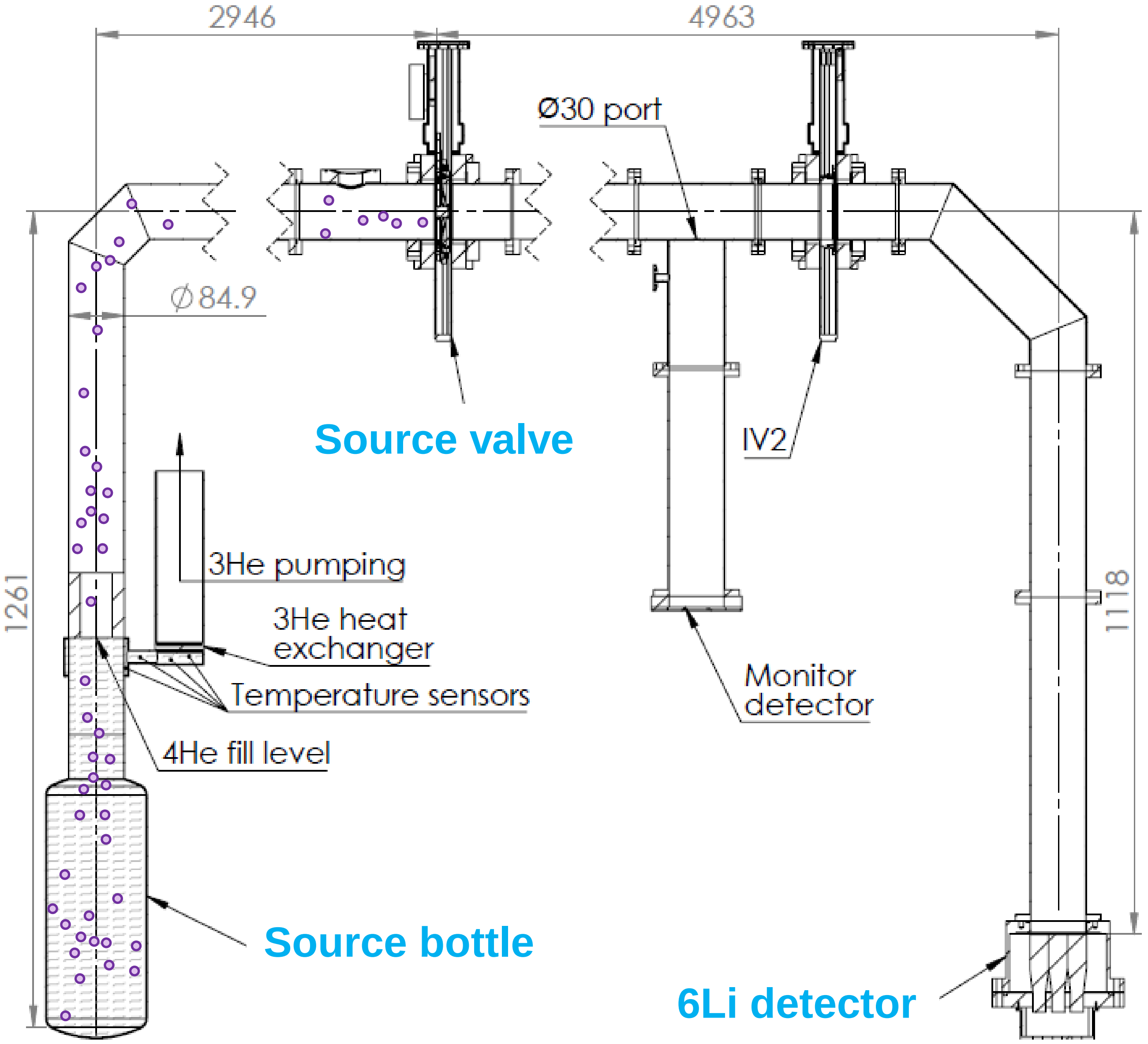

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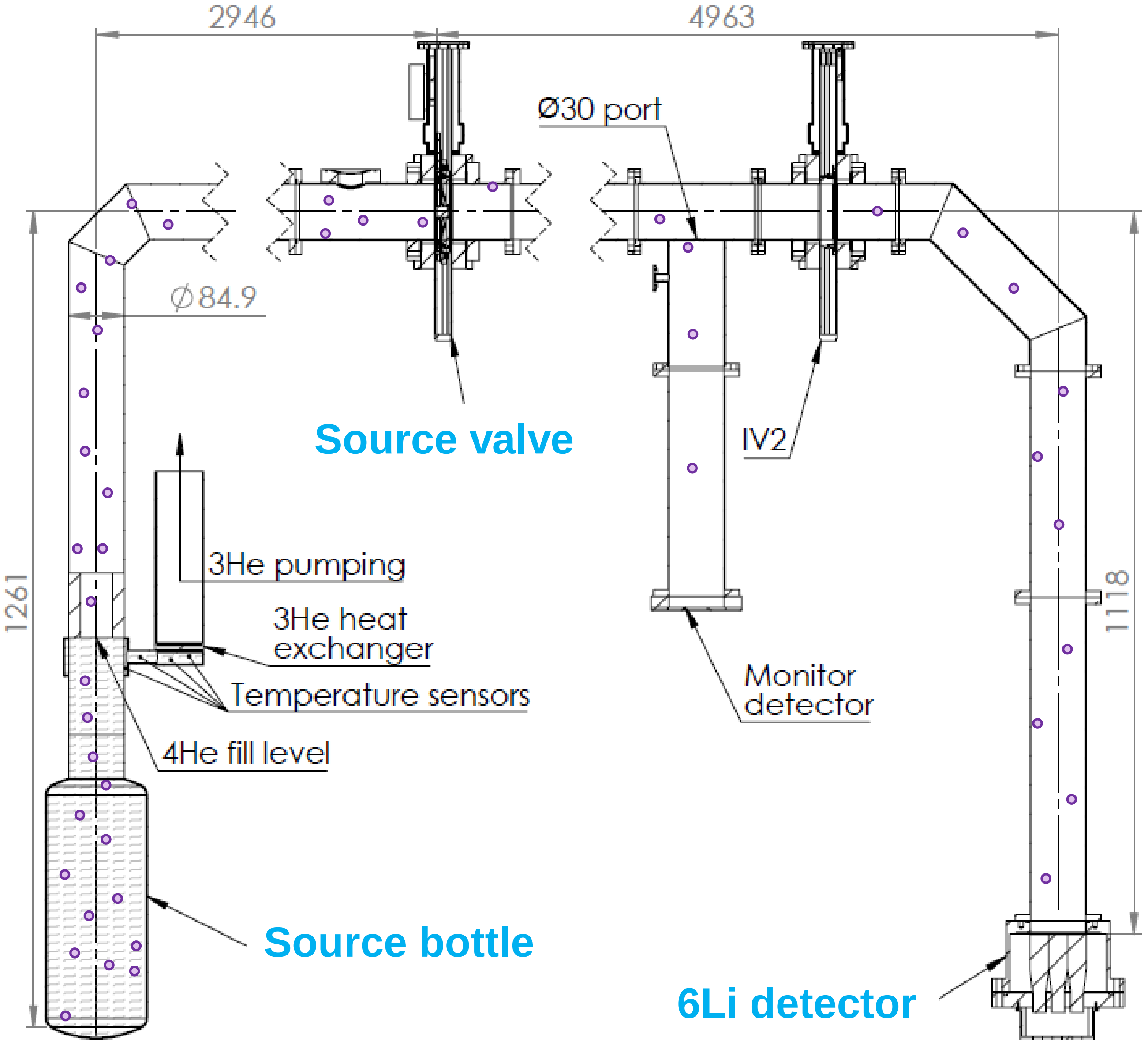


Source valve

Source bottle

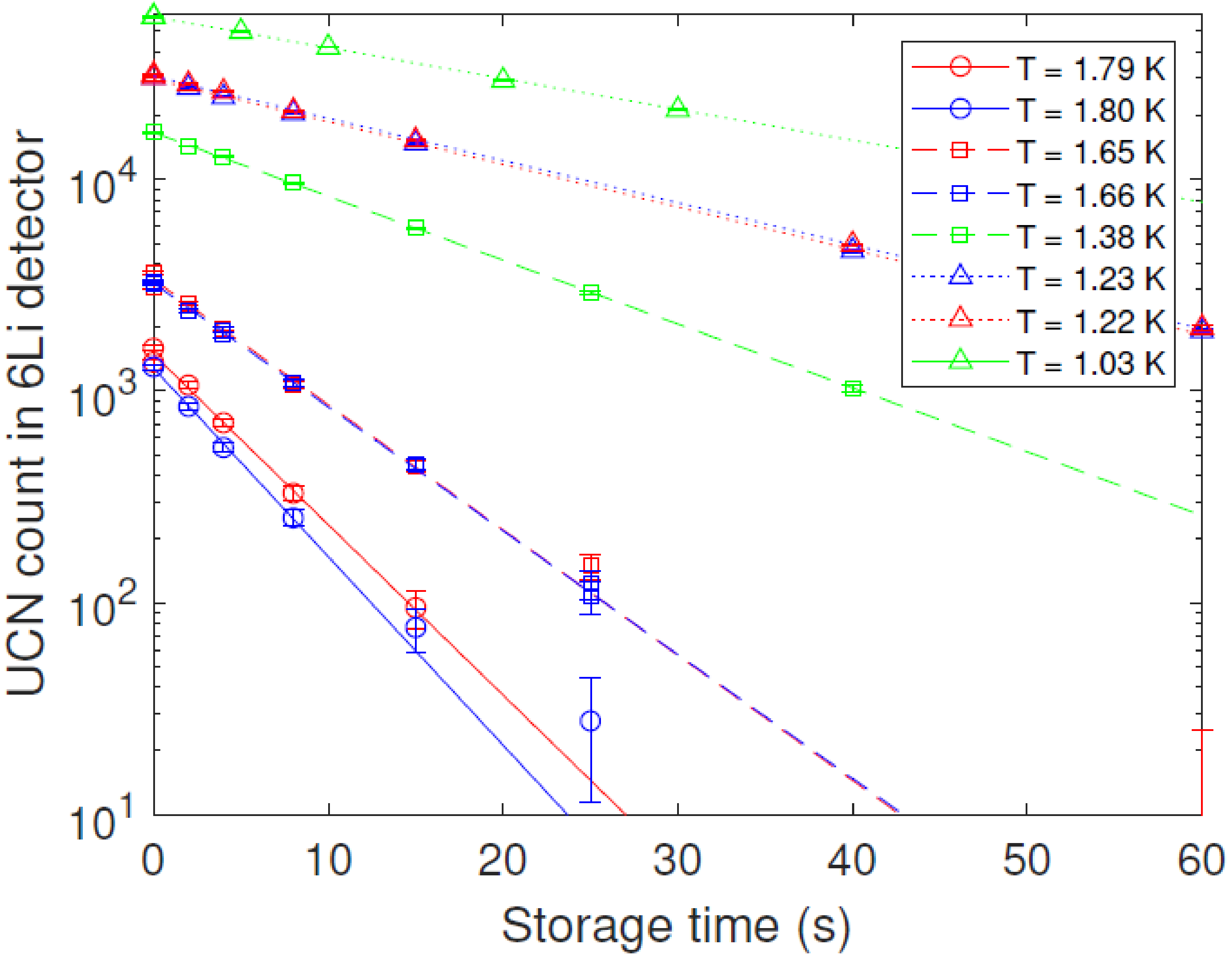
6Li detector

# Storage Lifetime Measurement

- Vary storage time to get storage lifetime $\tau$

- Vary temperature to get $\tau$ vs $T$

- Accurate vapour pressure measurement used to determine temperature



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# Storage Lifetime Measurement

The measured lifetimes are a combination of four loss channels

$$\tau^{-1} = f\tau_{\mathrm{He}}^{-1} + (1-f)\tau_{\mathrm{vapour}}^{-1} + \tau_{\mathrm{wall}}^{-1} + \tau_{\beta}^{-1}$$

Upscattering in He-II (weighted by fraction of time UCN spend in the liquid)

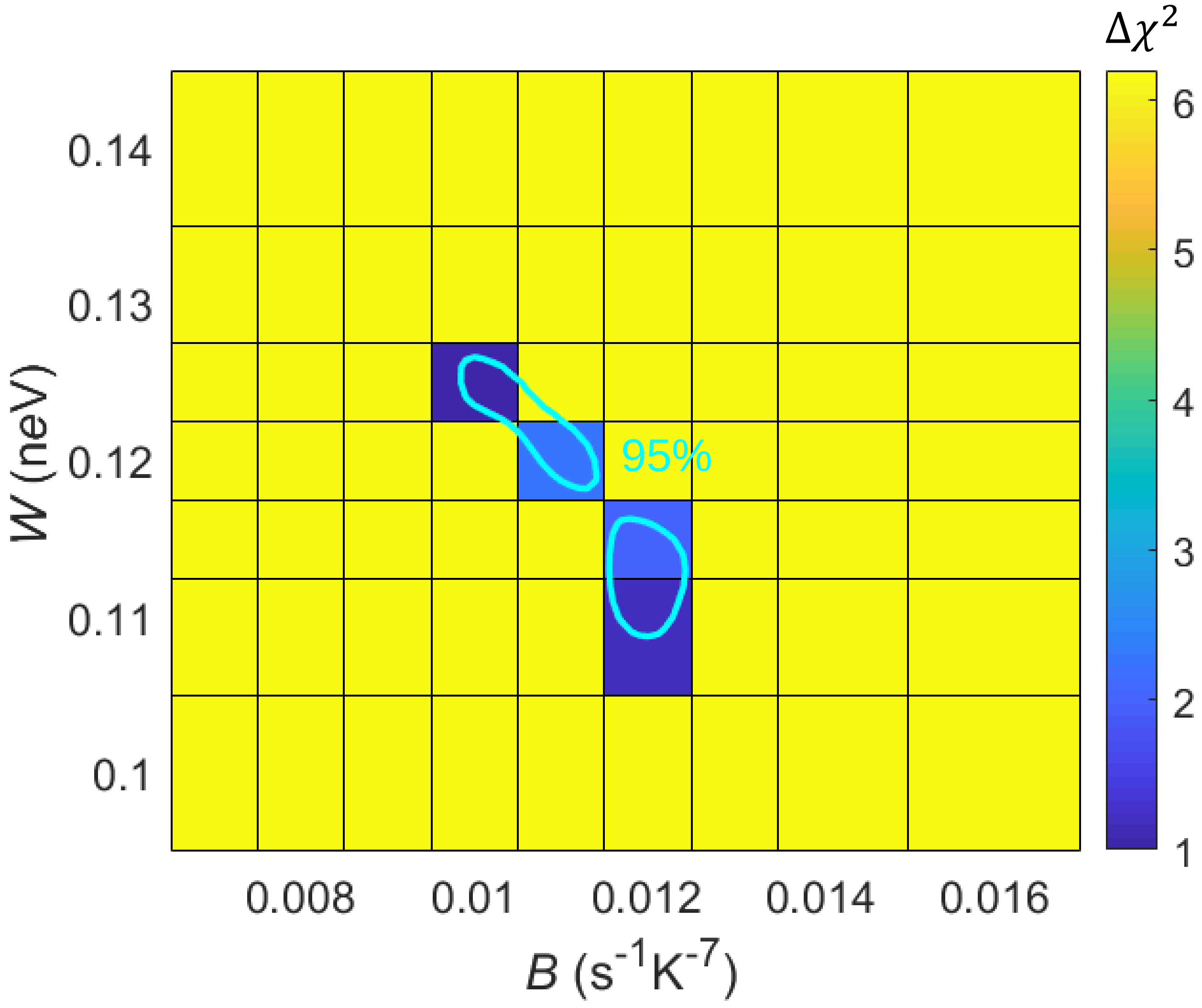
Losses in helium vapour (weighted by fraction of time UCN spend in the vapour)

Losses from wall collisions

Beta decay

Difficult to deal with analytically, so parameter fitting was done using Monte Carlo simulations

# Extracting *B*



- He-II losses *(B)* and wall collision losses ($\propto W$) are unknown parameters

- Find best-fit (*B*,*W*) by minimization of
$$\chi^2 = \sum_{i=1..8} \frac{(\tau_{\mathrm{exp}} - \tau_{\mathrm{sim}})^2}{\sigma_{\mathrm{exp}}^2 + \sigma_{\mathrm{sim}}^2}$$

- Each point = $40 \times 10^6$ UCN, spread across temperatures and storage times… requires years of CPU time!

- Results accept a narrow 95% CI of $0.010 < B < 0.012\ \mathrm{K}^{-7}\mathrm{s}^{-1}$!

# Summary

- UCN are a powerful probe of the standard model and new physics

- The TUCAN Source will use He-II to produce high densities of UCN

- Experimental reach is highly dependent on storage lifetime of UCN in He-II, determined by upscattering processes

- A successful measurement of storage lifetime was carried out at TRIUMF using a prototype source, indicating $0.010 < \mathrm{B} < 0.012\ \mathrm{K}^{-7}s^{-1}$, improving on previous results and providing good support for our predictions of source performance

- A publication of these results, with more details, is in preparation – stay tuned!

# Thank you!

TUCAN Collaboration, January 2023

*Sean Vanbergen*